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POLY-COIL DESIGN FOR A 60 TESLA QUASI-STATIONARY MAGNET

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1. INTRODUCTION

Among the new facilities to be offered by the National Science Foundation through the National High Magnetic Field Laboratory (NHMFL) are pulsed fields that can only be achieved at a national user facility by virtue of their strength, duration, and volume. In particular, a 44 mm bore pulsed magnet giving a 60 tesla field for 100 ms is in the final design stage. This magnet will be powered by a 1.4 GW motor-generator at Los Alamos and is an important step toward proving design principles that will be needed for the higher field quasi-stationary pulsed magnets that this power source is capable of driving.

The requirements for the magnet are

— produce a 60T flat-top pulse for 100 ms;
— have a recycle time of approximately 1 hour;
— provide a 77K bore of 44 mm;
— achieve field homogeneity of 10^{-3} or better in 10 mm sphere;
— be robust and reliable, with a lifetime of 10 years or 10,000 pulses for the outer coils and a lifetime exceeding 1000 pulses for the inner coils;
— permit higher field upgrades as better conductors or reinforcements become available;
— be operational by early 1995.

These requirements lead to a poly-coil design consisting of several mechanically independent and spatially separated coils with external reinforcing shells. Among the advantages:

—The reinforcement shell can be customized for each coil as needed to contain stress. This applies to both the hoop and axial stresses.

—Different conductors can be used in different regions.

—Independent power supplies can achieve fast rise times at lower voltage.

—Coils can be individually sized for efficiency without sacrificing homogeneity.

—Faster cooling occurs with separated coils.

—Individual coils are easily replaced to repair damage or install upgrades. (A possible upgrade path using a stronger conductor would be to substitute conductor turns for reinforcement thickness in one or more inner coils.)

—Conductive reinforcing shells can absorb energy from fast field transients caused by faults

—Failure may be confined to a small number of coils.

A disadvantage to the poly-coil approach is the loss of packing fraction and the consequent need for greater power. However, the NHMFL motor-generator removes available power as a design constraint and cost attention is devoted more to power control and conversion.

To permit timely delivery of the magnet, it was decided to design with conductor and reinforcement materials now commercially available. Tests by NHMFL have confirmed that GlidCop-60 and GlidCop-15, dispersion strengthened copper alloys manufactured by SCM Metal Products, Inc., are adequate conductors for the 60T magnet. .

2. DESIGN

The design evolved by manually iterating test solutions based on both discrete and averaged mechanical properties of the conductor-insulator coils in contact with reinforcing shells. A more automated iteration method was not attempted because of the difficulty of realistically including discrete and often unquantifiable design considerations related to fabrication, voltage-current, and thermal constraints.

For the most part, the design method follow that used by Lontai and Marston [1] to design the McGill University 10T magnet. This essentially treats the coil and shell as separate continua in a linear background field distribution at the midplane and solves the elastic equations for the hoop stress in the presence of a uniformly distributed Lorentz force in the coil. Only the midplane is treated. Other programs calculate the axial forces which can be included to yield the effective von Mises stress at the midplane. The effect of axial forces was included using results of Markiewicz *et al* [2] which show how axial stress is efficiently transferred to the reinforcing shell, especially in thin coils.

The results of the design are shown in Fig. 1 and Table 1. The identical current for the first seven coils does not imply a common power supply.

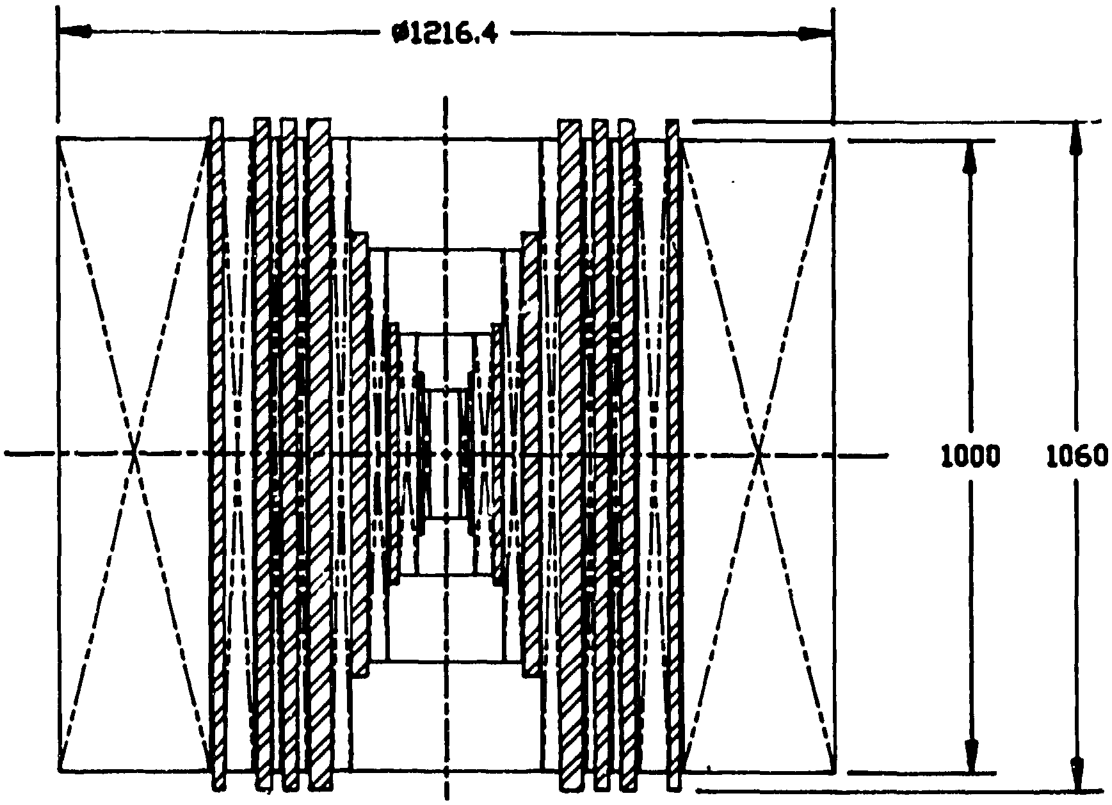

Figure 1 Eight-coil magnet. Dimensions are mm.

Table 1 Coil parameters. Dimensions are cm.

Coil	layers	turns	ID	OD	length	shell thick.	I, kA
1	2	46	4.75	7.26	20.2	0.6	18.6
2	4	144	9.06	14.9	38.	1.4	18.6
3	4	236	18.3	24.4	65.	2.5	18.6
4	4	360	30.0	36.1	100.	3.45	18.6
5	2	180	43.8	46.9	100	2.25	18.6
6	2	180	52.2	55.2	100	2.25	18.6
7	2	180	60.5	63.6	100	2.35	18.6
8	20	1260	69.1	116.3	100	0.	16.5

The packing factors, discounting the shells, are 0.65 for coil 1, 0.7 for coils 2 through 7 and 0.74 for coil 8. The total conductor mass is 5293 kg and the total reinforcing shell mass is 1527 kg. A 1-cm homogeneity of 1.3 10^{-4} is predicted.

3. MATERIALS

Realization of high field non-destructive magnets is materials limited: conductors of high strength, high conductivity, high specific heat, and good elongation; reinforcement material of high strength at 77K and superior fatigue strength; insulation of low compressibility, high viscosity and high thermal conductivity. The commercial materials chosen for the magnet are as follows.

Conductor: (Al-15 is used for coil 1, AL-60 for coils 2 through 8.)

	GlidCop AL-15	GlidCop AL-60
yield strength (0.2%) @ 77 K	594 MPa	745 MPa
ultimate strength @ 77 K	684 MPa	856 MPa
Young's modulus	139 GPa	143 GPa
elongation @ RT	12.5 %	9.2 %
elect. resistance ratio (77 K/RT)	4.84	3.98
%IACS conductivity @ RT	88.7	79.5
total thermal contraction, RT to 77 K	0.278 %	0.190 %

Reinforcement:

	Nitronic 40 (annealed)
yield strength (0.2%) @ 77 K	1.0 GPa
ultimate strength @ 77 K	1.4 GPa
fatigue strength (1000 cycles) @ 77 K	1. GPa
Young's modulus @ 77 K	186 GPa
elongation @ 77 K	23 %
elect. resistivity @ 77 K	63 micro-ohm-cm
thermal conductivity @ 77 K	7 W/mK
total thermal contraction, RT to 77 K	0.259 %

Insulation:

	CTD-101G	CTD-101 w/ 50% g
compression strength @ 77 K	560 MPa	1.25 GPa
compression modulus @ 77 K	17.7 GPa	
shear strength @ 77 K	170 MPa	200 MPa
shear modulus @ 77 K	8.2 GPa	9.1 GPa
thermal conductivity @ 77 K	10-20 W/mK	
total thermal contraction, RT to 77 K	0.4%	
viscosity @ 110 °C	2,000 cP	

The CTD-101G resin is 67% alumina by weight and has a remarkably high thermal conductivity. This makes it possible to cool coil 8 in one hour. The characteristics for CTD-101, which can be used for the thin coils, 1 through 7, refer to the impregnated composite of resin and 50% S-2 fiberglass. The conductor will be half-lapped with fiberglass and Kapton tape before being wound on the mandrel. The coils will then be potted in the usual manner, with the reinforcing shell used as part of the impregnation mold for some of the coils.

4. ELECTRICAL AND THERMAL BEHAVIOR

The design of the power supply for the 60 T magnet is a compromise between many parameters, such as coil stress and heating, modularity, upgrade capability and cost. The inner coils are designed for a shorter current pulse than the outer coil. Therefore, the coils are partitioned electrically into several groups. Although the seven inner coils have the same peak current, they must be partitioned further into two groups to avoid overheating the inner coils: the inner group comprising coils 1, 2, and 3 and the intermediate group of coils 4, 5, 6 and 7. Coil 8 is treated independently. Because of the strong influence of the mutual coupling, it was decided to keep the current in the outer groups nearly constant while the current in the inner group ramps up (Fig. 2). If the current in the inner coil group is ramped up while the outer groups are still ramping, a considerably higher voltage must be applied to maintain the ramp rate in the outer coils.

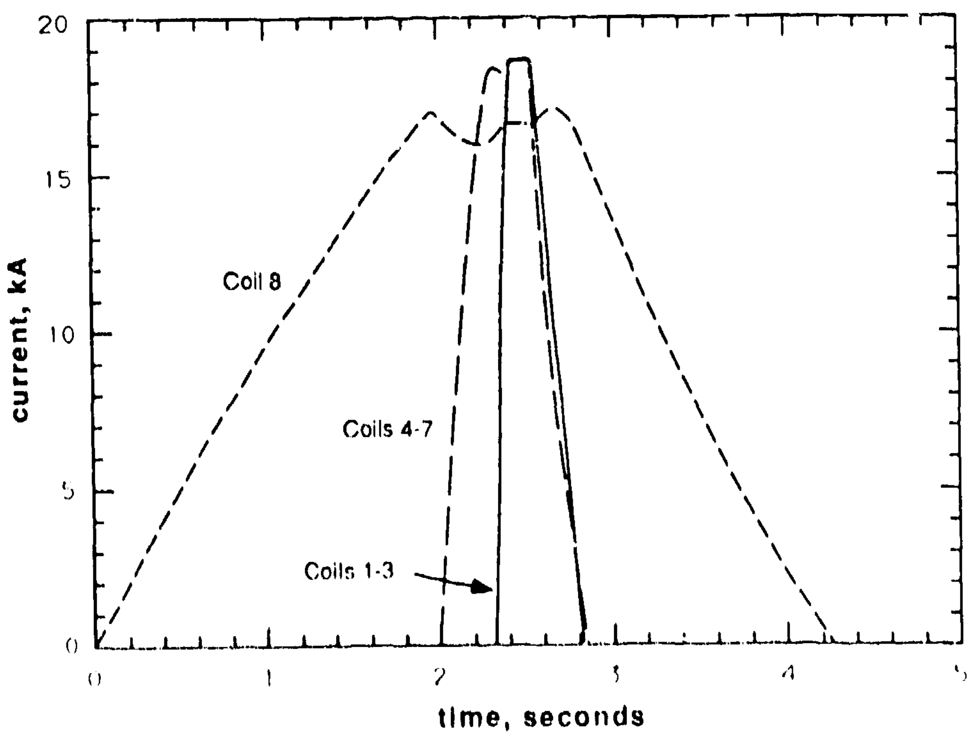

Figure 2. Desired current pulse in the three coil group.

Three power supplies are used for the three groups: coils 1-3, 4-7, and 8, respectively. Table 2 gives the peak current, I_p, voltage at the peak current, V, and the peak power requirement, P. The values of Table 2 are taken from simulation results. Coil 3 was included in the inner coil group to have enough inductance in the circuit to obtain an acceptable ripple value during the 60T, 100 ms flat top.

Given the peak current values and the required voltage values at peak current, the no-load voltage of the each supply can be determined. Assuming a 16% voltage drop between no-load and full-load voltage, the following no-load voltage, V_o, is obtained:

Supply 1	$V_o = 1.2$ kV
Supply 2	$V_o = 8.0$ kV
Supply 3	$V_o = 12.0$ kV

A 16% voltage drop for pulsed converters is a reasonable assumption. Supplies with such a voltage drop have been built for pulsed fusion experiments. A power supply with a no-load voltage in the range of 10 kV must be built up from several modules, which have no-load voltages in the range of 3 to 4 kV. Let us propose the higher voltage 4 kV design. The outer coil supply will need three modules, connected in series. The intermediate coils will need two modules connected in series. Each module is a 12 pulse unit, consisting of two series-connected 6 pulse units. Two 12 pulse modules can be arranged as one 24 pulse unit. However, because of the large inductance, the additional circuit complexity does not justify the small improvement in the ripple. Fig. 3 shows the supply module arrangement for the outer coil and the intermediate coils.

A module consists of a 24 kV circuit breaker, a three winding transformer, two series connected 6 pulse bridges and two 'thyristorised' crowbar paths. Each bridge has an output voltage of 2 kV and an input voltage of 1.5 kV. While the voltage rating of the two major supplies can be satisfied with identical modules, the current rating is different, because the current pulse length is different. The supply for the outer coil must be designed for a trapezoidal current with a 1.6 s rise and fall time and a 0.8 s flat top-time. Assuming a flat-top current

Table 2. Power Supply Parameters

	I_p	V	P
Supply 1 (coil 1, 2, 3)	18.64 kA	10.0 kV	18.64 MW
Supply 2 (coil 4, 5, 6, 7)	18.64 kA	6.6 kV	123.00 MW
Supply 3 (coil 8)	16.52 kA	10.0 kV	165.00 MW

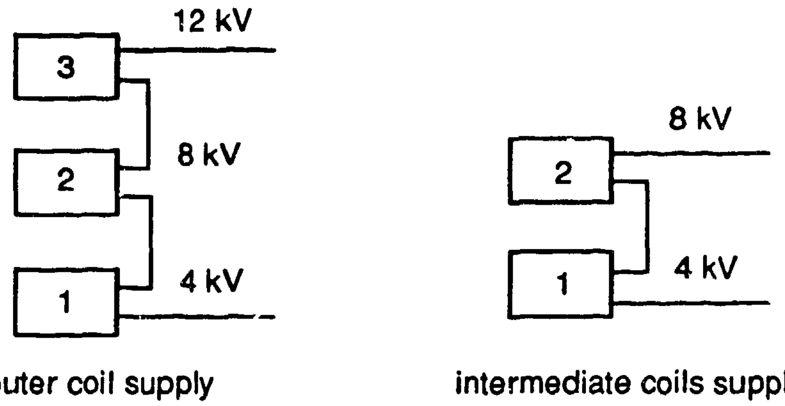

Figure 3. Power supply module arrangement for coil groups.

of 17 kA, the supply current must be dimensioned for an I^2t rating of $540 \cdot 10^6$ A^2S. An equivalent rectangular current with an amplitude of 17 kA and a pulse length of 2 s (1.866 s, more precisely) has the same heating effect.

The supply for the intermediate coils has a rise and decay time of about 0.3 s, a flat-top time of 0.225 s and a flat-top current of 18.6 kA. The equivalent rectangular pulse current with a 17 kA amplitude has a pulse length of 0.4s. If minimum cost is the only determining factor for purchasing the power supplies, NHMFL will have two different types of power supply modules for the 60T magnet. Considering the fact that a facility is being built which should supply power for magnets above 60T with increased power requirements the preferred choice is to buy 12 pulse, 4 kV, 20 kA, 2 s pulse length modules. These modules can be connected in parallel and series to accommodate different requirements.

The inner coil group will be supplied by an existing 12 pulse power supply. Each power supply should be equipped with a free wheeling path, made of thyristors.

Power supplies generate voltage ripple when the bridge converters are phased back, resulting in a lower average output voltage. At the beginning of the flat top the average coil voltages are the smallest, resulting in the highest ripple voltages. If the simplest converter control strategy is used to achieve the reduction in average voltage, the ripple current can be calculated to be $2.5 \cdot 10^{-3}$, $0.3\ 10^{-3}$ and $5.5\ 10^{-3}$ for the field produced by the inner, intermediate and outer coil group respectively. Table 3 gives the assumption for the ripple calculation with V_0 the supply no-load voltage, V the average voltage at the beginning of the flat-top, V_{pp12} and I_{pp12} the peak to peak 12^{th} harmonic voltage and current, L the inductance of the coil group and R the ratio of I_{pp12} to the flat-top current, Imax. All the values are approximated. As expected, the inner coil group doesn't have enough inductance to smooth out the current. Some advanced converter control for the inner coil group supply can reduce the ripple to $5 \cdot 10^{-4}$.

Table 3. Ripple Calculation

	V_o	V	V_{pp12}	L	I_{pp12}	I_{max}	R
Supply 1	1.2 kV	0.45 kV	0.7 kV	5.00 mH	41 A	18.64 A	$2.5 \cdot 10^{-3}$
Supply 2	8.0 kV	4.70 kV	3.0 kV	0.15 H	6 A	18.64 kA	$3.0 \cdot 10^{-4}$
Supply 3	12.0 kV	3.80 kV	8.0 kV	0.80 H	3 A	16.50 kA	$1.7 \cdot 10^{-4}$

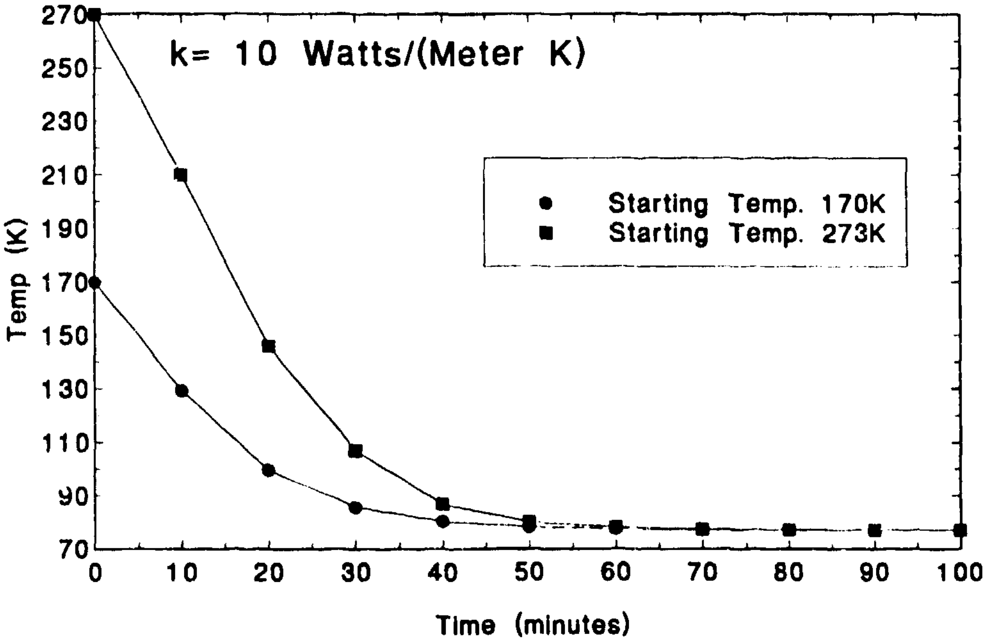

Figure 4 Cooling time for outermost coil.

The critical thermal behavior is the final coil temperature, because the epoxy insulation degrades at temperatures modestly above room temperature. In this design, no coil reaches such temperatures. Also, Fig. 4 shows the thickest coil easily cools to 77 K in an hour, satisfying an important user requirement.

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